APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: MONITORING MECHANISMS FOR OPTICAL SYSTEMS

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MONITORING MECHANISMS FOR OPTICAL SYSTEMS

[0001]   This application claims the benefits of U.S.

Provisional Application Nos. 60/454,450 entitled

5   "MONITORING MECHANISMS FOR OPTICAL SYSTEMS" and filed March

12, 2003, and 60/493,880 entitled "SOP GENERATOR AND

ANALYZER BASED ON TUNABLE OPTICAL POLARIZATION ROTATORS"

and filed August 8, 2003. The entire disclosures of the

above two-referenced applications are incorporated herein

10   by reference as part of the disclosure of this application.

Background

[0002]   This application relates to optical monitoring in

optical devices and systems.

15   [0003]   Optical properties or parameters of light in an

optical device or system may be measured for various

purposes. As an example, such an optical measurement may

be used to determine the performance or an operating

condition of the device or system. An optical property or

20   parameter of light under measurement may include the

optical polarization, the signal to noise ratio, the

differential group delay between two orthogonal

polarization states, and others.

[0004]   The optical polarization is an important

25   parameter of an optical signal in various optical systems.

For example, in fiber optic communication systems, polarization-dependent effects in fibers and other devices, such as polarization-dependent loss (PDL) and polarization-mode dispersion (PMD), can have significant impacts on

5   performance and normal operations of optical devices or systems. Hence, it may be desirable to measure and monitor the degree of polarization (DOP) of an optical signal in these and others systems.

[0005]   Similarly, the signal-to-noise ratio (SNR) and

10 the differential group delay (DGD) of an optical signal are also important parameters and hence monitoring of these parameters may be desirable under certain circumstances.

Summary

[0006]   This application includes various implementations and examples of devices and techniques for monitoring the SNR, DOP, and DGD of one or more optical signals. In one implementation, an optical scrambler and a polarizer may be used in the optical path for the measurements. In another implementation, a rotatable quarter waveplate and a rotatable half waveplate are used in the optical path for the measurements. In yet another implementation, a state-of-polarization generator and a linear polarizer may be used for the measurements. The optical monitoring devices described here may be used to measure WDM channels.

[0007]   These and other implementations and applications are described in greater detail in the attached drawings, the detailed description, and the claims.

Brief Description of the Drawings

[0008]   FIGS. 1 and 2 show two exemplary optical

monitoring devices with a polarization scrambler or

controller.

5   [0009]   FIG. 3 shows an implementation of the monitoring

device in FIG. 2 in a transmission system.

[0010]   FIG. 4 shows a monitoring setup for a wavelength-

division-multiplexed (WDM) transmission line where the

input includes signals at different WDM wavelengths.

10   [0011]   FIG. 5 shows one implementation of an all-fiber

dynamic PMD controller 500 based on the above monitoring

techniques.

[0012]   FIG. 6 shows one implementation of a

microprocessor-based monitoring device.

15   [0013]   FIG. 7 shows a monitoring device that uses a WDM

demultiplexer in the output of the polarization scrambler

or controller to separate different WDM channels.

[0014]   FIG. 8 shows another implementation where a

diffraction grating is used to separate different WDM

20   channels.

[0015]   FIG. 9 shows one implementation of a PMD-

insensitive monitoring device for WDM applications where

only a single polarization scrambler is used for all

wavelength channels.

[0016]   FIG. 10 shows another implementation of a WDM monitoring device where a single polarization beam splitter is combined with two WDM demultiplexers.

[0017]   FIG. 11 shows a system having a real-time DGD monitoring device and a dynamic PMD compensator.

[0018]   FIG. 12 illustrates the processing operation by a DGD processing circuit in FIG. 11 with reference to the Poincaré sphere for the polarization.

[0019]   FIGS. 13, 14, and 15 show three examples of optical monitoring devices that use a rotatable quarter waveplate and a rotatable polarizer as a polarization scrambler.

[0020]   FIG. 16 shows a fiber system that uses a Fabry-Perot filter and sequential or parallel multi-channel polarimeters to monitor the SOP of each channel.

[0021]   FIG. 17 illustrates operations of the Fabry-Perot filter in FIG. 16.

[0022]   FIGS. 18A and 18B show two examples of WDM optical monitoring devices that use a rotatable quarter waveplate and a rotatable half waveplate as part of the device.

[0023]   FIGS. 19A, 19B, 19C, 19D, and 19E illustrate examples of optical monitoring devices that use a SOP generator and a fixed optical polarizer.

[0024]   FIGS. 20 and 21 show exemplary implementations of a SOP generator.

[0025]   FIG. 22 shows a device that uses a SOP generator to measure the degree of polarization of light.

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Detailed Description

[0026]   FIG. 1 illustrates one exemplary implementation

of a monitoring device 100 for monitoring both SNR and DOP

in the received light. The monitoring device 100 may use a

5   fiber to receive an optical signal 101 under monitoring,

and an optical loop 120 such as a fiber loop to perform the

monitoring. An optical coupler 110, such as a 50% fiber

coupler, may be coupled to the two ends of the fiber loop

120 to split the input signal 101 into two counter-

10   propagating beams in the loop 120 and to combine the two

counter-propagating beams to produce an output beam 140.

Hence, the coupler 110 and the loop 120 provides a

mirroring mechanism. A polarization scrambler or

controller 130 is placed in the fiber loop 120 to either

15   randomly scramble the polarization of light in the loop 120

or to systematically control the polarization to vary

through all possible states of polarization so that a

maximum power level and a minimum power level in the output

beam 140 can be found. The scrambler or controller 130 may

20   be optionally controlled in response to a control signal

163 to adjust the state of polarization of light passing

therethrough.

[0027]   In one implementation of the device 130 as

illustrated in FIG. 1, the polarization scrambler or

controller 130 may include two or more fiber squeezers 131

and 132 respectively under control of the controllers 133

and 134. The squeezing directions of the fiber squeezers

131 and 132 are oriented to be 45 degrees with respect to

5   each other to perform the scrambling operations.

[0028]   An optical detector 150 may be coupled to receive

the output light 140 from the loop 120. An optional

optical isolator 103 may be placed in the path of the input

beam 101 to prevent any optical feedback to the input path.

10 A processing circuit 160 is coupled to receive the detector

output from the detector 150 to produce an output signal

162 which includes information about the SNR or DOP.

[0029]   In operation, the detector 150 detects the

maximum and the minimum optical power levels in the output

15 signal 140. The processing circuit 160 can be designed to

compute the extinction ratio based on measured maximum and

the minimum optical power levels. In various applications,

the signal 101 is generally polarized and the noise is not

polarized. Hence, the extinction ratio can directly relate

20 to the SNR and DOP. As the extinction ratio increases, the

DOP and the SNR increase accordingly, and vice versa. The

processing circuit 160 may also includes a control unit

that controls the operation of the polarization scrambler

130.

[0030]   FIG. 2 shows a monitoring device 200 based on another implementation. The polarization scrambler 130 is placed to scramble the input light 101 and a polarizer 210 is used to transmit the output light of the scrambler 130.

5   The polarizer 210 is used here to replace the mirroring loop 120 in the monitoring device 100 in FIG. 1. The optical detector 150 is then used to receive the transmitted light from the polarizer 210. The processing circuit 160 receives and processes the detector output to

10   produce the output 162.

[0031]   FIG. 3 shows an implementation of the monitoring device 200 in a transmission system 300. An optical coupler 310 is placed in the path of the input beam 301 to tap a fraction of the input 301 as a monitoring beam 320

15   and the remaining 302 of the input 301 continues along the input path as an output of the system 300. The monitoring device 200 is coupled to receive the monitoring beam 320 to perform the measurement. Notably, a housing 303 may be used to enclose the coupler 310, the path for the

20   monitoring beam 320, and the monitoring device 200. All optical paths may be fibers, dielectric waveguides, or a combination of fiber paths and waveguide paths. The housing may be hermetically sealed to provide an integrated package for deployment in a fiber transmission line or

system. A substrate may be used to fabricated waveguides

and other optical components in a single-chip package

enclosed within the housing 303. It is understood that,

the monitoring device 100 in FIG. 1 may also be used to

5   replace the device 200 in FIG. 3 and other systems shown in

this application.

[0032]   FIG. 4 shows a monitoring setup for a wavelength-

division-multiplexed (WDM) transmission line where the

input 301 includes signals at different WDM wavelengths.

10   The coupler 310 may split all WDM signals at the input to

produce the monitoring beam 320. A WDM coupler may be used

as the coupler 310. A tunable optical filter 410 is

coupled between the coupler 310 and the monitoring device

200 or 100 to sequentially filter the WDM signals so that

15   only one signal at a single WDM wavelength is transmitted

to the device 200 or 100. As the filter 410 is tuned

sequentially through all signal wavelengths, one at a time,

each and every WDM signal is measured by the device 200 or

100. A control device 420 may be implemented and coupled

20   to the filter 410 and the monitoring device 200 or 100 to

control such sequential filtering and monitoring

operations. The tunable filter 410 may be implemented in a

number of configurations, such as a tunable Fabry-Perot

filter, a tunable fiber grating filter (e.g., coupled with

a fiber stretcher), multiple filters with different

transmission wavelengths on a rotation wheel which may be

controlled by a step motor, and others.

[0033]   FIG. 5 shows one implementation of an all-fiber

5   dynamic PMD controller 500 based on the above monitoring

techniques.   An adjustable polarization controller 510 is

coupled in the input fiber to control the polarization of

the input beam 501.   A polarization-maintaining fiber

segment 520 is coupled to the output of the polarization

10   controller 510 to produce the desired differential group

delay in the output light from the controller 510.   Fiber

fusion splicing may be used to connect the PM fiber segment

510.   A fiber coupler 310 is used to split the output of

the controller 510 into an output beam 502 in the input

15   fiber and a monitoring beam 320 to the monitoring device

200 in FIG. 2 (or the device 100 in FIG. 1) for monitoring

the degree of polarization.   The circuit 160 is coupled to

supply the output 162 to control the polarization

controller 510 so that the polarization controller 510 can

20   be dynamically adjusted in response to the measurement by

the circuit 160.   The polarization controller 510 may be

implemented in various configurations.   The PMD controller

500 may include multiple, e.g., three or more, fiber

squeezers.   U.S. Patent No. 6,493,474 to Yao on December

10, 2002 discloses some examples based on four sequential fiber squeezers and is incorporated herein in its entirety as part of this application.

[0034]   The system in FIG. 5 may be used to achieve a number of advantages, such as low optical loss at less than 0.5dB and low cost due to the unique designs based on simple optical layout and simple components. A hermetically-sealed housing 530 may be implemented as illustrated.

[0035]   FIG. 6 shows one implementation of a microprocessor-based monitoring device 600. A polarization controller 630 is used to adjust the SOP of the input light 612 under monitoring and a polarizer 210 is used to transmit the output light of the controller 630 to an optical detector 150. The output signal 152 from the detector 150 may be electrically amplified by an amplifier 660 and the amplified signal is sent to a microprocessor-based processing circuit 650. The processing circuit 650 converts each received analog signal into digital bits and performs the signal processing operations by using a microprocessor in the digital domain. An output 651 is then produced to indicate the monitoring result on either the DOP or the SNR of the light 612. As illustrated, a

laser 610 or other light source may be used to produce the input light 612.

[0036]   Optionally, a beam splitter 620, such as a fiber coupler, may be used to split a fraction of the input beam 612 as a reference beam 622 to a second optical detector 640. This beam splitter 620 should be insensitive to the light polarization. The output 642 of the second detector 640 is then fed into the circuit 650 for processing. This reference beam 622 provides a measurement of the power variation in the input beam 612 so that a part of the variation in the received signal 152 caused by the power variation alone may be deducted from the variation caused by the polarization change caused by the scrambler 630.

[0037]   In operation, the circuit 650 may produce a control signal 652 to adjust the controller 630 in search for the maximum power (V_{max}) and the minimum power (V_{min}) at the detector 150. The control signal 652 may be digitally generated by the microprocessor and then converts into an analog signal. Based on measurements on the Vman and Vmin, the processor in the circuit 650 computes the DOP or SNR of the light. The DOP may be computed as follows:

$$DOP = \frac{V_{max} - V_{min}}{V_{max} + V_{min}}.$$

[0038]   The polarization controller 630 may use a two-
squeezer design as the element 130 in FIG. 1 or a three-
squeezer design as illustrated in FIG. 6, or five- or six-

5   squeezers to provide increased control in adjusting the SOP
of input light. FIG. 6 shows a termination design where
the input beam is entirely used for the monitoring
operation. Alternatively, the monitoring device 600 may be
implemented as an in-line package similar to the design in

10   FIG. 3 where an additional splitter 310 is used to split
the main input beam 301 to produce the input to the
monitoring device 600 and the remaining of the main input
beam continues to propagate in the transmission system.

[0039]   In the above and other monitoring devices in this

15   application, a tunable optical filter may be inserted in
the input path to allow for sequential monitoring of
different WDM channels in the input. FIG. 4 shows one
example. This multi-channel technique based on a tunable
filter can be implemented in various monitoring devices of

20   this application. However, this technique is limited to
sequential monitoring of one channel at a time.

[0040]   FIGS. 7 and 8 illustrate two multi-channel
monitoring techniques for simultaneous monitoring of

different WDM channels. Such techniques allows for taking

snap shots of different channels at the same time.

[0041]   FIG. 7 shows a monitoring device 700 that uses a

WDM demultiplexer 710 in the output of the polarization

5   scrambler or controller 130 to separate different WDM

channels. In the optical path of each separate WDM

channel, a polarizer 210 and an optical detector 150 are

used to receive and detect the power levels of each

channel. Hence, power levels of different channels can be

10   measured at the same time. The output signals from the

detectors 150 are then fed into the circuit 160 for data

processing to monitor the WDM channels. Multiple

polarizers 210 are placed in the optical paths between the

dmux 710 and the detectors 150. Alternatively, a single

15   polarizer may be placed between the polarization scrambler

130 and the WDM demultiplxer 710 to replace with multiple

polarizers 210 in front of the detectors 150.

[0042]   FIG. 8 shows another implementation 800 where a

diffraction grating 820 is used to separate different WDM

20   channels. A collimator 810 is used to receive the output

of the polarization scrambler 130 to produce a collimated

output. A polarizer 210 is placed between the polarization

scrambler 130 and the collimator 810. The grating 820

diffracts the input light at different WDM wavelengths at

different diffraction angles. This diffraction spatially

separates different WDM channels. A second collimator 830,

such as a lens, is used to collect the diffracted beams of

different channels and focus the diffracted beams onto

5   different detector elements of an array of optical

detectors 840. A processing circuit 850 may be optionally

used to condition the detector output signals prior to the

circuit 160.

[0043]   The above monitoring devices based on a

10   polarization scrambler may be sensitive to the PMD in the

input signal that includes two or more WDM channels. This

sensitivity on the PMD may cause an error in the

measurement. In general, the greater the PMD in the input,

the larger the error of the monitoring device. Hence, it

15   may be desirable to mitigate this PMD effect in monitoring

the DOP or SNR.

[0044]   FIG. 9 shows one implementation of a PMD-

insensitive monitoring device 900 for WDM applications

where only a single polarization scrambler is used for all

20   wavelength channels. The device 900 includes a universal

polarization scrambler 910 to receive input WDM channels in

an input fiber 901. One or more optical amplifiers 902 may

be used in the input optical path to amplify the input WDM

channels. A WDM demultiplexer 920 is used to receive the

output from the scrambler 910 and to split different WDM

channels by their wavelengths as separate optical output

signals 922. In each optical output, a polarizing beam

splitter (PBS) 930 or a suitable polarization device is

5   used to split the received light based on their two

orthogonal polarizations to produce two beams with

orthogonal polarizations. A bandpass filter 940 is used to

filter one of the two outputs of the PBS 930 so that the

power levels of the noise power levels in two output beams

10   are different while the power levels of the signals in the

output beams are essentially unaffected by the filtering.

As illustrated, the filter 940 may be positioned to filter

light from the port that transmits light along the

direction of the input beam.

15   [0045]   The above optical filtering causes an imbalance

between the noise power levels in the two output beams with

orthogonal polarizations. This imbalance is used for

simultaneous and independent monitoring of both SNR and

DOP. Two orthogonally oriented polarizers 941 and 942 may

20   be optionally placed at the two output ports of the PBS 941

to ensure the output beams are orthogonally polarized. Two

optical detectors 951 and 952 are positioned to receive the

two outputs of the PBS 930, respectively. The output

signals of the detectors 951 and 952 are fed into a

processing circuit 970 for measurements and data

processing. Two electrical signal amplifiers 961 and 962

may be optionally used to amplify the detector outputs,

respectively, prior to the processing by the circuit 970.

5   [0046]   In one implementation, the bandpass filter 940

may have a bandwidth broader than the actual bandwidth of

each signal channel to allow each signal channel to pass

without filtering but narrower than the bandwidth of the

WDM device for each channel to filter out some noise

10   components to create the power imbalance in the noise

between the two output beams. For example, for WDM

channels with a 100 GHz in the channel spacing and 10GHz in

the channel bandwidth, the WDM demultiplexer 920 may be

designed to have a channel bandwidth 50GHz. The bandpass

15   filter 940 may have a bandwidth of 25GHz, between the 10-

GHz channel bandwidth and 50-GHz device channel bandwidth,

to allow a channel to pass without being filtered.

However, the noise components outside the 25GHz window are

filtered out in the transmitted beam of the PBS 930.

20   [0047]   The maximum and minimum detected power of all SOP

detected at the two detectors 951 and 952 are:

$$\begin{cases} V_1^{max} = G_1[P_s(1-\delta)+0.5P_N] & (1) \\ V_1^{min} = G_1[P_s\delta+0.5P_N] & (2) \\ V_2^{max} = G_2[P_s(1-\delta)+0.5\alpha P_N] & (3) \\ V_2^{min} = G_2[P_s\delta+0.5\alpha P_N] & (4) \end{cases}$$

where P_s is the signal power, P_N is the noise power, α is less than 1 and is the noise power filtering factor of the bandpass filter 940, and δ the depolarization factor caused by, e.g., the PMD in the input signal, the nonlinear birefringence, and imperfection of the PBS 930. Notably, in absence of the filter 940 which produces the an inbalance between the two output beams from PBS 930, the Eqs. (1) and (2) would be identical to Eqs.(3) and (4). The filter 940 is specifically used to break the degeneracy and to provide separate measures of SNR and DOP.

[0048]   Equations (1) and (2) are added to obtain the following:

$$V_1^{max} + V_1^{min} = G_1(P_S + P_N) \quad (5),$$

Equations (1) and (2) are subtracted:

$$V_1^{max} - V_1^{min} = G_1 P_s(1-2\delta) \quad (6).$$

Similar manipulations of Equations (3) and (4) yield:

$$V_2^{max} + V_2^{min} = G_2(P_s + \alpha P_N) \quad (7)$$

$$V_2^{max} - V_2^{min} = G_2 P_S(1-2\delta) \quad (8)$$

Additionally, the following signal processing can be carried out:

$$G_2 \cdot Eq.(5) - G_i \cdot Eq.(7) = G_2 \left(V_1^{max} + V_1^{min} \right) - G_1 \left(V_2^{max} + V_2^{min} \right)$$

$$= G_1 G_2 P_S + G_1 G_2 P_N - G_1 G_2 P_S - \alpha G_1 G_2 P_N.$$

Hence, the following can be obtained:

$$G_1 G_2 (1 - \alpha) P_N = G_2 \left(V_1^{max} + V_1^{min} \right) - G_1 \left(V_2^{max} + V_2^{min} \right), \text{ and}$$

$$P_N = \frac{1}{1 - \alpha} \left[\frac{V_1^{max} + V_a^{min}}{G_1} - \frac{V_2^{max} + V_2^{min}}{G_2} \right] \qquad (9)$$

5   From Eq.(5), the following can be derived:

$$G_1 P_S = \left(V_1^{max} + V_1^{min} \right) - G_1 P_N$$

$$= \left(V_1^{max} + V_1^{min} \right) - \frac{1}{1 - \alpha} \left[\left(V_1^{max} + V_1^{min} \right) - \frac{G_1}{G_2} \left(V_2^{max} + V_2^{min} \right) \right]$$

$$= \left(1 - \frac{1}{1 - \alpha} \right) \left(V_1^{max} + V_1^{min} \right) + \frac{G_1 / G_2}{1 - \alpha} \left(V_2^{max} + V_2^{min} \right)$$

$$= \frac{1}{1 - \alpha} \left[\frac{G_1}{G_2} \left(V_2^{max} + V_2^{min} \right) - \alpha \left(V_1^{max} + V_1^{min} \right) \right].$$

Therefore, the following expressions can be derived:

$$P_S = \frac{1}{1 - \alpha} \left[\frac{V_2^{max} + V_2^{min}}{G_2} - \frac{\alpha}{G_1} \left(V_1^{max} + V_1^{min} \right) \right] \qquad (10)$$

$$S / N = \frac{P_s}{P_N}$$

$$= \frac{\dfrac{V_2^{max} + V_2^{min}}{G_2} - \dfrac{\alpha}{G_1} \left(V_1^{max} + V_1^{min} \right)}{\dfrac{V_1^{max} + V_1^{min}}{G_1} - \dfrac{V_2^{max} + V_2^{min}}{G_2}}$$

$$= \frac{G_1 \left(V_2^{max} + V_2^{min} \right) - \alpha G_2 \left(V_1^{max} + V_1^{min} \right)}{G_2 \left(V_1^{max} + V_1^{min} \right) - G_1 \left(V_2^{max} + V_2^{min} \right)}.$$

10   Let $\overline{V_1} = \frac{1}{2} \left(V_1^{max} + V_1^{min} \right)$, and

$$\overline{V}_2 = \frac{1}{2}\left(V_2^{max} + V_2^{min}\right),$$

the SNR can be computed as follows:

$$\frac{S}{N} = \frac{G_1\overline{V}_2 - \alpha G_2\overline{V}_1}{G_2\overline{V}_1 - G_1\overline{V}_2}. \qquad (12)$$

If $G_1 = G_2$, then SNR becomes

5
$$\frac{S}{N} = \frac{\overline{V}_2 - \alpha\overline{V}_1}{\overline{V}_1 - \overline{V}_2}.$$

Hence, the signal to noise ratio only depends on the

average V_1 and V_2. This approach essentially excludes all

the effects of PMD, the nonlinear birefringence, and the

PBS imperfection.

10   **[0049]**   From Equations (6), (9), and (10), the

depolarization factor δ can be calculated as:

$$G_1 P_S\left(1 - 2\delta\right) = V_1^{max} - V_1^{min},$$

$$1 - 2\delta = \frac{1}{G_1 P_S}\left(V_1^{max} - V_1^{min}\right), \text{ and}$$

$$\delta = \frac{1}{2}\left[1 - \frac{1}{G_1 P_S}\left(V_1^{max} - V_1^{min}\right)\right] = \frac{1}{2}\left[1 - \frac{\left(1-\alpha\right)\left(V_1^{max} - V_1^{min}\right)}{\frac{G_1}{G_2}\left(V_2^{max} + V_2^{min}\right) - \alpha\left(V_1^{max} + V_1^{min}\right)}\right].$$

15   For $G_1 = G_2$, the depolarization factor can be simplified as:

$$\delta = \frac{1}{2}\left[1 - \frac{\left(1-\alpha\right)\left(V_1^{max} - V_1^{min}\right)}{2\left(\overline{V}_2 - \alpha\overline{V}_1\right)}\right].$$

[0050] The contribution to δ from the imperfection of the PBS 930 can be eliminated by placing polarizers 941 and 942 at the outputs of the PBS 930 in FIG. 9. Accordingly, the depolarization caused by PMD can be precisely measured.

5 This mechanism may also be used to monitor PMD effect.

[0051] The device in FIG. 9 uses multiple PBSs for the separated WDM channels. Alternatively, FIG. 10 shows another implementation 1000 where a single PBS 930 is combined with two WDM demultiplexers 1010 and 1020. In

10 this design, the two demultiplexers 1010 and 1020 may be purposely designed to be different to introduce the noise power imbalance with a factor of $\alpha(\lambda i)$ (i=1, 2, …, N). For example, the device channel bandwidths of the two demultiplexers 1010 and 1020 may be different, e.g., one is

15 50 GHz and the other is 75 GHz for WDM signals with a channel bandwidth of 10GHz and a channel spacing of 100GHz, where each WDM channel transmits without being attenuated but the noise power levels of the same channel in the outputs of the demultiplexers 1010 and 1020 are different.

20 Hence, the filter 940 in FIG. 9 may be eliminated. If the two demultiplexers 1010 and 1020 are identical, then the filtering is needed to introduce the power imbalance.

[0052] Now turning to FIG. 11, a real-time DGD monitoring mechanism is shown in the fiber system 1100 and

is used in connection with a dynamic PMD compensator. The

fiber system includes three main modules: a transmitter

terminal, the fiber transmission line 1103 which may

include a fiber link with optical amplifiers, and a

5   receiving terminal. The transmitter terminal may include

multiple optical transmitters 1101 at different channel

wavelengths and a WDM multiplexer 1102 to multiplex the

different channels for transmission in the fiber link 1103.

The receiving terminal includes a DGD monitor, a

10   demultiplexers 1120, dynamic PMD compensators for different

channels, and optical receivers 1180 for different

channels. An optical coupler 1110, such as a fiber

coupler, may be placed in the input of the demultiplexer

1120 to split a fraction of the input signal as a monitor

15   beam 1112 to the DGD monitor and the main input signal is

received by the demultiplexer 1120.

[0053]   The DGD monitor in the system 1100 includes a

tunable filter 1130, a polarimeter 1140, and a DGD

processing circuit within a control unit 1190. The filter

20   1130 is tuned to sequentially scan through different WDM or

DWDM channels to allow for different channels to reach the

polarimeter 1140, one at a time. The bandwidth of the

filter 1130 is sufficiently narrower than the bandwidth of

each channel. The polarimeter 1140 is operable to measure

the SOP at a high speed for the real-time monitoring. The

DGD processing circuit within the control unit 1190

receives and processes the SOP signal generated by the

polarimeter 1140 to determine the DGD in each channel.

5　[0054]　　In operation, the tunable filter 1130 is tuned to

a channel at its center wavelength λi and is scanned around

λi for a duration longer than the time for the polarimeter

1140 to measure the SOP of that channel. During this

scanning around λi, the polarimeter processes the input

10　optical signal at λi to produce the information on the SOP

of this channel.

[0055]　　FIG. 12 illustrates the processing operation by

the DGD processing circuit with reference to the Poincaré

sphere for the polarization. Let the angular variation in

15　the SOP angle around the principal axis Ω be $\Delta\theta i$ for the

channel λi, and the frequency tuning range around the center

wavelength λi be $\Delta f i$, the DGD can be calculated as follows:

$$\Delta\tau_i = \frac{\Delta\theta_i}{2\pi\Delta f_i}.$$

This calculation is performed by the DGD processing

20　circuit. FIG. 12 shows that, both the DGD and direction of

the principal axis Ω can be determined.

[0056]   Next, the control unit 1190 uses the DGD

information to control the PMD compensator to produce a DGD

that negates this measured DGD. This completes the

monitoring and control operation on one channel. The

5   control unit 1190 then commands the filter 1130 to tune to

the next channel to repeat the monitoring and compensation

operation. This process repeats for all channels

sequentially.

[0057]   The DGD monitoring mechanism in FIG. 11 is shared

10   by all channels. The PMD compensation, however, is

implemented individually for each channel. Hence, multiple

PMD compensators are used in the example in FIG. 11 for

different channels, respectively. Only one compensator for

the channel λ1 is depicted for simplicity.

15   [0058]   In the optical path for each channel after the

demultiplexer 1120, the PMD compensator for that channel is

placed before a respective channel receiver 1180. The PMD

compensator may include an optical polarization controller

(PC) 1150, a variable DGD (VDGD) element 1160 to produce a

20   variable DGD, a DOP monitor 1170 for measuring the degree

of polarization of the light, and a PMD control circuit

within the control unit 1190. The polarization controller

1150 may use various implementations, including the fiber-

squeezer controllers disclosed in the incorporated U.S.

Patent No. 6,493,474. The DOP monitor 1170 may be

configured to tap a portion of the signal for the

monitoring operation and send the remaining signal to the

channel receiver 1180. As illustrated, the PMD control

5 circuit controls both the polarization controller 1150 and

the variable DGD element 1160 in response to the measured

DOP from the monitor 1170. Hence, the control is a

feedback control and operates dynamically to produce real-

time PMD compensation. In implementations, a

10 microprocessor may be used in the control unit 1190 to

perform the computations for the DGD measurement and the

PMD compensation.

[0059] The polarimeter 1140 in FIG. 11 may be

implemented in various configurations. FIG. 13 shows one

15 exemplary implementation 1300 by using a rotatable quarter-

wave plate 1310 and a rotatable polarizer 1320 to

sequentially process input light. The plates 1310 and 1320

are controlled, e.g., by the circuit 1350, to rotate at

different rotational speeds or frequencies. In this and

20 other implementations, the rotatable wave plate 1310 may be

replaced by a polarization controller such as the fiber-

squeezer controller disclosed in the attached US Patent No.

6,493,474. An optical detector 1330 converts the processed

light into a detector signal and a signal processing

circuit 1350 further processes the detector signal to

measure the SOP of the light. A signal amplifier 1340 may

be optionally coupled between the detector 1330 and the

circuit 1350 to amplify the signal. Hence, in the

5   configuration in FIG. 11, as the filter 1130 scans through

different channels, the polarimeter 1300 measures the SOP

one channel at a time. Alternatively, the configuration in

FIG. 11 may be modified to place the tunable filter 1130

between the detector 1330 and the polarizer 1320 of the

10   polarimeter 1300.

[0060]   A polarimeter may also be configured to measure

SOP of multiple channels in parallel at the same time.

FIGS. 14 and 15 show two examples. In FIG. 14, the

polarimeter 1400 uses a demultiplexer 1120 to separate

15   different channels output by the quarter-wave plate 1310

and the polarizer 1320. For each channel, a designated

optical detector 1330 and a designated signal processing

circuit 1350 are used to process the channel signal to

determine the SOP of that channel. Hence, all channels are

20   monitored in parallel with one another at the same time.

[0061]   FIG. 15 shows a different design 1500 where a

diffraction grating 820 and a collimating lens 830 are used

to spatially separate the different channels in a manner

similar to the design in FIG. 8 for a different

application. A processing circuit 1520 is used to process

the detector outputs to produce the SOP signals for

different channels.

[0062]   In absence of PMD in an input optical signal, the

5   SNR of the signal can be directly determined from the DOP

measurement. Assume P_s is the power of the signal which is

polarized and P_n is the power of the noise which is

unpolarized. The DOP can be computed by the following

equation:

10

$$DOP = \frac{P_s}{P_s + P_n} = \frac{P_s/P_n}{1 + P_s/P_n}.$$

Accordingly, the SNR can be computed from DOP:

15       $$SNR = \frac{P_s}{P_n} = \frac{DOP}{1 - DOP}.$$

Here, the DOP can be computed from the maximum and minimum

power levels from the measurements. When DOP is 1, the SNR

is infinite and when DOP is zero, the SNR is zero.

20   [0063]   FIG. 16 shows a fiber system 1600 that uses any

one of the above sequential or parallel multi-channel

polarimeters to monitor the SOP of each channel. A fiber

coupler 1110 is used to split a fraction of the input light

with multiple channels to produce a monitor beam 1112. A

tunable Fabry-Perot filter 1610 is used to filter the

monitor beam 1112 to transmit all WDM channels at the same

5 time to a multi-channel polarimeter 1620. This may be

accomplished by designing the Fabry-Perot filter 1610 to

have a free spectral range (FSR) equal to the channel

spacing of the WDM channels or a multiplicity of the

channel spacing. In operation, the tunable Fabry-Perot

10 filter 1610 is tuned to measure the DGD as illustrated in

FIG. 12. FIG. 17 further shows the spectrum of the filter

1610 where a tuning in the filter 1610 causes the same

amount of frequency shift in the transmission of all

channels. The polarimeter 1620 may be a sequential multi-

15 channel polarimeter having a tunable filter or a parallel

multi-channel polarimeter as shown in FIGS. 14 and 15.

[0064] In some WDM systems, the channel spacing may be

50GHz, 100GHz, or 200 GHz. Assuming the finesse of the

filter 1610 is 100, the resolution bandwidth of the filter

20 is 1 GHz and should be sufficient to resolve the spectrum

of a 10Gb/s signal. As described above, the DGD of each

channel can be calculated based on the measured SOP in each

channel as illustrated in FIG. 12.

[0065]   FIGS. 18A and 18B show two exemplary

implementations 1801 and 1802 for providing independent

monitoring of the signal to noise ratio (SNR) and DGD in

WDM systems. In both systems, the input light is

5   sequentially processed by a rotatable quarter-wave plate

1310 and a rotatable half-wave plate 1810. The waveplates

1310 and 1810 rotate at different rotation speeds. Also in

both systems, each channel is split into two beams with

orthogonal polarizations to have different power levels.

10   In the system 1801, this is achieved by using two different

demultiplexers 1010 and 1020 with different channel

bandwidth. In the system 1802, a filter 940 is inserted in

one of the two output beams to produce the difference. The

processing techniques in connection with FIGS. 9 and 10 are

15   applicable here.

[0066]   In the above described examples shown in FIGS.

13, 14, 15, 18A and 18B, the polarization scrambler formed

by the rotatable waveplate 1310 and the rotatable polarizer

1320 may be replaced by a SOP generator and a downstream

20   fixed optical polarizer. The SOP generator may be used to

manipulate the polarization of received light to produce

any desired SOP.

[0067]   FIGS. 19A, 19B, 19C, 19D, and 19E illustrate

examples 1901, 1902, 1903, 1904, and 1905 of optical

monitoring devices that use a SOP generator 1910 and a

fixed optical polarizer 1920. The SOP generator 1910 may

be configured to be adjustable to produce various SOPs. An

external control signal may be used to control the SOP

5   generator 1910 in producing SOPs.

[0068] FIG. 20 shows one example of a SOP generator. In

this example, the SOP generator includes four controllable

polarization rotators 1, 2, 3, and 4 that are sequentially

placed in the optical path. A quarter waveplate is placed

10   between the rotators 2 and 3. In addition, an optional

input polarizer may be placed in front of the first rotator

1 for aligning the input polarization with respect to the

optical axis (c-axis) of the $\lambda/4$ plate. The input polarizer

may be oriented in various directions, e.g., aligned with

15   the c-axis, or 45° from the c-axis, or other predetermined

angle. Each of the polarization rotators in FIG. 20 may be

individually controlled by a control signal as illustrated.

Polarization rotations of the rotators are controlled to

produce the desired SOPs at the output.

20   [0069] In one implementation, each polarization rotator may

be a magneto-optic (MO) rotator to avoid any mechanical

moving part in the SOP generator. This use of MO rotators

or other polarization rotators without moving parts can

improve the reliability and operating life of the device.

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[0070] A polarization rotator, such as a MO rotator, suitable for the SOP generator in FIG. 20 may be designed to have the following properties: (1) When applying a positive voltage above saturation voltage Vsat (V ≥ +

5 Vsat), the rotator rotates the SOP by +22.5°; (2) When applying a negative voltage above saturation voltage Vsat, (V ≤ - Vsat), the rotator rotates the SOP by -22.5°; (3) When rotators 1 and 2 (or 3 and 4) are rotated in the same direction, the net rotation of the pair of rotators 1 and 2

10 or rotators 3 and 4 is 45°; and (4) When rotators 1 and 2 (or 3 and 4) are rotated in the opposite directions, the net rotation of the pair is 0°.

[0071] Accordingly, this particular SOP generator can be used to generate at least the following states of

15 polarization when the input SOP is linear and is aligned with the c-axis of the 1/4 plate:

(1) Linear SOP at 0° when 1 & 2 are rotated at opposite directions and 3 & 4 are rotated at opposite directions;

20 (2) Linear SOP at +45° when rotators 1 and 2 are rotated at opposite direction, but rotators 3 and 4 are rotated by +22.5° each;

(3) Linear SOP at -45° when rotators 1 and 2 are rotated at opposite direction, but rotators 3 and 4 are rotated by -22.5° each;

(4) RHC (right hand circular) when rotators 1 and 2 are rotated by +22.5° each; and

(5) LHC (left hand circular) when rotators 1 and 2 are rotated by -22.5° each.

[0072] TABLES 1 and 2 are logic tables for two configurations of the SOP generator in FIG. 20.

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TABLE 1. Input SOP is aligned with quarter wave plate

Rotator 1	Rotator 2	Rotator 3	Rotator 4	SOP
+ 22.5°	- 22.5°	+ 22.5°	- 22.5°	0° linear
+	-	-	+	0° linear
-	+	+	-	0° linear
-	+	-	+	0° linear
+	-	+	+	45° linear
-	+	+	+	45° linear
+	-	-	-	-45° linear
-	+	-	-	-45° linear
+	+	+	+	RHC
+	+	-	+	RHC
+	+	+	-	RHC
+	+	-	-	RHC
-	-	+	+	LHC
-	-	-	+	LHC
-	-	+	-	LHC
-	-	-	-	LHC

TABLE 2. Logic table for SOP generation
(Input SOP is aligned 45° from c-axis of the quarter wave plate

Rotator 1	Rotator 2	Rotator 3	Rotator 4	SOP
+ 22.5°	- 22.5°	+ 22.5°	- 22.5°	RHC
+	-	-	+	RHC
-	+	+	-	RHC
-	+	-	+	RHC
+	-	+	+	RHC
-	+	+	+	RHC
+	-	-	-	·RHC
-	+	-	-	RHC
+	+	+	+	45° linear
+	+	-	+	0° linear
+	+	+	-	0° linear
+	+	-	-	-45° linear
-	-	+	+	45° linear
-	-	-	+	0° linear
-	-	+	-	0° linear
-	-	-	-	-45° linear

[0073] FIG. 21 shows an example of a packaged SOP generator based on the design in FIG. 20 where the generator is

5 packaged or pigtailed with PM or single mode (SM) fibers. As illustrated, a housing may be used to hold the rotators and the waveplate along with the optional input polarizer.

Two fiber collimators may be used at the input and output

ports of the SOP generator and may be engaged to the input

and output PM or SM fibers. The fibers may also be single

mode PM fibers.

5   [0074] In operating the SOP generator in FIG. 20 or 21, the

SOP of an input light signal may be determined by

performing the following steps: 1) Insert a polarizer at 0°

and measure the optical power after the polarizer; 2)

Rotate the polarizer by 45° and measure the optical power

10   after the polarizer; 3) Rotate the polarizer by 90 (or -

45°) and measure the optical power after the polarizer; and

4) Insert a right-hand-circular (RHC) or left-hand-circular

(LHC) polarizer and measure the optical power after the

polarizer.

15   [0075] Alternatively, the SOP of the input optical signal

may also be measured by the following steps: 1) Insert a

polarizer at 0° and measure the optical power after the

polarizer; 2) Rotate the SOP by 45° and measure the optical

power after the polarizer; 3) Rotate the SOP by 90 (or -

20   45°) and measure the optical power after the polarizer; and

4) Convert the SOP to RHC (or LHC) and measure the optical

power after the polarizer.

[0076] The above SOP generator can therefore be used to

measure the SOP and DOP of the signal. FIG. 22 shows one

exemplary setup for such a measurement. An output

polarizer is placed at the output of the SOP generator and

an optical detector is used to receive and measure the

power of the output from the output polarizer. This SOP

5   generator may be used to generate the required 4

polarization states for the polarizer to analyze.

[0077]   These and other implementations, variations,

modifications, and enhancements are possible.

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